

### Temperature independent low reference voltage source

The invention relates to a temperature independent low reference voltage source, comprising a low voltage source, being proportional to the absolute temperature, with the reference voltage at the output of the voltage source according to the invention lying within a technically important temperature range considerably below 1 volt and for the source according to the invention requires a supply voltage lying considerably below 1 volt.

Almost each integrated circuit uses a source of temperature independent reference voltage to perform various functions. A reference voltage source based on an extraction of silicon-energy-gap potential needs supply voltage exceeding 1.2 V. In order to make battery supply at a voltage of 1,2 V or below applicable various reference voltage sources, otherwise based, have been proposed.

The patent US 5,614,816 describes a circuit of a temperature independent low reference voltage source, the summing circuit of which combines divided down voltage of a bipolar junction and multiplied voltage of a source (PTAT source), the voltage of which is proportional to the absolute temperature. The described circuit should be supplied with supply voltage ranging near 0.9 V or below and generates reference voltage lying near 0.9 V or below. It uses an operational amplifier, which enters nonideal behaviour due to offset voltage. Furthermore, a threshold voltage difference of MOS transistors is applied as the bipolar junction voltage, although it is known that the temperature properties of bipolar transistors and those of MOS transistors are different.

Further temperature independent low reference voltage sources are described in patents US 5,325,045 and 6,225,856. They comprise an operational amplifier needing a higher supply voltage due to input in-phase voltage as well as due to the required supply voltage. Said supply voltage exceeds even 2 V, because inner voltages, such as  $V_{be}$  voltage across a diodelike forward connected bipolar transistor or  $V_t$  threshold voltage of a MOS transistor are summed.

None of said reference voltage sources is applicable at a really low supply voltage lying below 0.7 V, which appears to be a serious limitation, for a battery voltage drops at an increased instantaneous load and is lower at low temperatures and in an exhausted battery.

Consequently, the technical problem to be solved by the present invention is how to construct an integrated low reference voltage source, the reference voltage being temperature independent, in a way that the reference voltage will be really low and the source will need a low supply voltage, however, it will comprise an assembly of electronic elements, controlled only by temperature and joining two complementary temperature variations as well as possessing self-regulation properties.

Novel features considered characteristic of this invention are set forth with particularity in the appended claims.

The source of temperature independent low reference voltage of the invention is distinguished for its the current controlled summing regulator, which is also suggested by the invention, and which makes it possible that in a temperature range from  $-50^{\circ}\text{C}$  to  $150^{\circ}\text{C}$  a very low reference voltage of 0.35 V at low supply voltage lying below

0.9 V is reached and does simultaneously not introduce nonideal behaviour typical of an operational amplifier.

The invention will now be explained in more detail by way of description of two embodiments and with reference to the accompanying drawing and graphs representing in:

Fig. 1 schematic presentation of a source having temperature independent low reference voltage according to the first embodiment of the invention,

Fig. 2 schematic presentation of a current controlled summing regulator according to the second embodiment of the invention,

Fig. 3 graph of temperature dependence of the first and the second current flowing into the current controlled summing regulator according to the invention,

Fig. 4 a graph of the temperature dependence of a current flowing through a diodelike forward connected transistor in the current controlled summing regulator according to the first embodiment of the invention at supply voltage of 0.9 V and the reference voltage of 0.35 V,

Fig. 5 graph of temperature dependence of a current flowing through first resistor and of temperature dependence of a current flowing through second resistor in the current controlled summing regulator according to the first embodiment of the invention at supply voltage of 0.9 V and reference voltage of 0.35 V,

Fig. 6 a graph of the temperature dependence of a reference voltage at the output of the source of a low temperature independent reference voltage according to the first embodiment of the invention at supply voltage of 0.9 V, and

Fig. 7 a graph of the supply voltage dependence of a reference voltage at the output of the source of temperature independent low reference voltage according to the first embodiment of the invention at temperatures  $-50^{\circ}\text{C}$ ,  $50^{\circ}\text{C}$  and  $150^{\circ}\text{C}$ .

A circuit of a source having temperature independent low reference voltage  $V_r$  according to the invention consists of a voltage-to-current converter VCC comprising among other elements a low voltage source (a low voltage PTAT source), the voltage  $V_{PTAT}$  of which is proportional to the absolute temperature and a resistor  $R$ , as well as of a current-to-voltage converter  $t$ , current generators  $t1$ ,  $t2$  and of a current controlled summing regulator CCSR (Fig. 1).

It is important for the source circuit of the invention it is important that the PTAT voltage source comprised in the voltage-to-current converter VCC is a low voltage source and that the resistor  $R$ , also comprised therein, is integrated in the n.-well technology in the same way as a first resistor  $R_a$  and a second resistor  $R_b$  are integrated in the current controlled summing regulator CCSR. Furthermore, the circuit of the voltage-to-current converter VCC must be designed in a way that the current-to-voltage converter  $t$ , connected between said converter and a  $V_{dd}$  terminal of a high-supply voltage, produces a control potential  $V$  at the input of said converter VCC, the temperature characteristics of which control potential  $V$  includes temperature properties of a quotient  $V_{PTAT} / R$  between the voltage  $V_{PTAT}$  of the PTAT-voltage source and the resistance of the resistor  $R$ .

According to the invention the first current generator  $t1$  and the second current generator  $t2$  are controlled by said control potential  $V$  so that they generate the first current  $I1$  and the second current  $I2$ , respectively, the temperature characteristics whereof are equal to the temperature characteristics of said quotient  $V_{PTAT} / R$ . The first current  $I1$  and the second current  $I2$  are conducted to a first input terminal  $X$  and to a second input terminal  $Y$ ;  $Y'$ , respectively, in the current controlled summing regulator CCSR.

Preferably, the first current generator  $t1$  and the second current generator  $t2$  are selected in a way that the second current  $I2$  is higher than the first current  $I1$ .

The first current  $I_1$  is conducted to the first terminal X on the first connection of a composition of series connected first resistor  $R_a$  and the second resistor  $R_b$ . The second connection of said resistor composition is grounded. Between the first terminal X and the ground the bipolar transistor T; T' is diodelike forward connected, as it will be explained later with regard to a specific embodiment. The second current  $I_2$  is conducted to a second terminal Y, which is preferably a common connection Z of the first resistor  $R_a$  and the second resistor  $R_b$ , in a variant embodiment it is conducted to the sliding second terminal Y' on the second resistor  $R_b$  to allow adjustment of the reference voltage  $V_r$ . The common connection Z of the first resistor  $R_a$  and the second resistor  $R_b$  simultaneously represents the output of the source of a temperature independent low reference voltage  $V_r$  according to the invention.

In the first embodiment of the source of a temperature independent low reference voltage  $V_r$  according to the invention an emitter of the vertical bipolar pnp transistor T is connected to said first terminal X, whereas the collector and base of said transistor are grounded.

In the second embodiment of the source of a temperature independent low reference voltage  $V_r$  according to the invention a MOS transistor T' is connected between said first terminal X and the ground like a diode (Fig. 2).

The current-to-voltage converter t controls the first and the second current generators  $t_1$ ,  $t_2$ , the current generators  $t_1$ ,  $t_2$  acting as a current mirror and being implemented as forward connected MOS transistors.

The circuit according to the invention in the described embodiments is implemented in the  $0.6\ \mu\text{m}$  standard CMOS technology. It can function at the supply voltage  $V_{dd}$  below 0.8 V; the lowest supply voltage in the first embodiment is equal to the sum of the voltage across the current generator and the voltage  $V_{be}$  of the conductively

polarized base-emitter junction in the vertical bipolar transistor, amounting to 0.6 V at the room temperature, and in the second embodiment, when implemented just by means of MOS transistors, it is equal to the sum of the highest threshold voltage  $V_t$  of the transistor and of the double saturation voltage of the transistor channel, *i. e.* 0.85 V at  $-50^\circ\text{C}$  and 0.6 V at  $150^\circ\text{C}$ . The supply voltage  $V_{dd}$  is higher at low temperatures - in Fig. 7 the supply voltage  $V_{dd}$  dependence of the reference voltage  $V_r$  at temperatures  $-50^\circ\text{C}$ ,  $50^\circ\text{C}$  and  $150^\circ\text{C}$  is represented for the first embodiment - and *vice versa*, because at lower temperature the voltages  $V_{be}$  and  $V_t$  are lower. The circuit of the invention in the first embodiment provides reference voltage of 0.35 V and in the second embodiment 0.55 V and its value does not change noticeably with the supply voltage  $V_{dd}$  (Fig. 7). Without any adjusting the reference voltage remains practically constant in the temperature range from  $-50^\circ\text{C}$  to  $150^\circ\text{C}$ . Power consumption of the circuit of the invention is  $1\mu\text{W}$  or less.

The source of a temperature independent low reference voltage  $V_r$  according to the invention functions as follows.

The whole second current  $I_2$  conducted to the second terminal Y in the current controlled summing regulator CCSR from the second current generator  $t_2$  flows into the second resistor  $R_b$  -  $I_a$  being positive (Fig. 5) - below temperature  $T^*$ , when the voltage  $V_{be}$  of the conductively polarized base-emitter junction in the vertical bipolar transistor T (the first embodiment) is higher than the reference voltage  $V_r$  on the connection Z. The second current  $I_2$  contributes to the voltage across the second resistor  $R_b$  proportionally to  $V_{PTAT}$ . The first current  $I_1$  conducted to the current controlled summing regulator CCSR from the first current generator  $t_1$ , in the first terminal X, branches into a current  $I_a$ , acting as regulation current within the current controlled summing regulator CCSR and flowing through the resistors  $R_a$  and  $R_b$  to the ground, and into a current  $I_{be}$  flowing into the emitter of the vertical bipolar transistor T. The temperature dependence of the first current  $I_1$  and of the second

current  $I_2$  for the supply voltage of 0.9 V in the first embodiment is represented in Fig. 3. The voltage  $V_{be}$  is set up by the current  $I_{be}$  - its temperature dependence at the supply voltage of 0.9 V is represented in Fig. 4 - and its temperature coefficient is therefore negative. Below the temperature  $T^*$  the voltage  $V_{be}$  exceeds the reference voltage  $V_r$ , being equal to the voltage drop of the sum of the currents  $I_2$  and  $I_a$  across the second resistor  $R_b$ , by the voltage drop of the current  $I_a$  across the first resistor  $R_a$ . The current  $I_a$  is regulated by means of the voltage  $V_{be}$  ( $I_a = V_{be}/(R_a + R_b)$ ) and has temperature properties of  $V_{PTAT}$  and of the resistors within the circuit. Said summing and regulation result in the reference voltage  $V_r$  which is not temperature dependent.

It is evident from Fig. 4, that  $I_{be}$  increases faster at a lower temperature than at a higher temperature. With the temperature increasing the current  $I_a$  into the resistor  $R_a$  decreases, above the temperature  $T^*$ , however, the direction of the current  $I_a$  is reversed (Fig. 5) and also part of the second current  $I_2$  contributes to the current  $I_{be}$ . With the temperature increasing also the voltage  $V_{be}$  decreases at a rate of 2 mV/K and finally the resistance of the resistors  $R_a$ ,  $R_b$  increases at a rate of  $0.007\text{ K}^{-1}$ . Due to an equally high positive temperature coefficient of the resistance of the resistor  $R$  the first current  $I_1$  and the second current  $I_2$  significantly decrease, when the temperature increases, and the increase of the current  $I_{be}$  becomes slower. The source of a temperature independent low reference voltage  $V_r$  according to the invention functions correctly up to the temperature so high, up to which that part of the second current  $I_2$ , flowing as the current  $I_b$  through the second resistor  $R_b$ , is sufficient to generate reference voltage  $V_r$ . Preferably the first current  $I_1$  is adjusted to be lower than the second current  $I_2$  in both embodiments.

Temperature stability of the reference voltage  $V_r$  (Fig. 6) in the circuit of the invention is achieved by correction of negative temperature dependence of  $V_{be}$  or  $V_t$  of the diodelike-connected transistor  $T$ ;  $T'$  by means of temperature dependent voltage decrease on the second resistor  $R_b$  due to a current, as defined by  $V_{PTAT}$ , and of a

steep exponential dependence of the current  $I_{be}$ . On the other hand, the level of the voltage  $V_{be}$  is adjusted with respect to a level of the reference voltage  $V_r$ .

Low and temperature independent reference voltage  $V_r$  is achieved by means of the current controlled summing regulator CCSR owing to the following characteristics of the circuit of the invention: the resistors  $R$ ,  $R_a$ ,  $R_b$  have a high positive temperature coefficient; both members of the regulation loop and the summing feedback loop are regulated by the currents  $I_1$  and  $I_2$ , the generation of which is controlled by the quotient  $V_{PTAT} / R$ ; by the regulated voltage in the feedback loop through  $R_a$  regulates the current  $I_{be}$ , whereby the temperature dependence of the voltage  $V_{be}$  is linearized. A double regulation loop is built in, which is controlled solely by temperature:  $I_1 / I_a = f_1(V_{be})$  and  $V_{be} = f_2(I_1 - I_a)$ .

In the second embodiment of the circuit according to the invention the threshold voltage  $V_t$  of the diodelike connected MOS transistor  $T'$  is established on the first terminal  $X$ . Channel saturation voltage is low, which is achieved by a large geometry of the transistor  $T'$  and by a current  $I_{ds}$ , which guarantees operation in a sub-threshold regime.

Figs. 1 and 2 show a modification of the circuit of the first and second embodiment, which in a preferable way allows adjustment of the reference voltage  $V_r$ , in that the second current  $I_2$  is conducted to the appropriate terminal  $Y'$  on the second resistor  $R_b$ . In this way the regulation loop of the circuit of the invention is preserved and the voltage of the fixed member can be adjusted digitally. The relation  $I_2/I_1$  of the second and first currents is preserved and the current  $I_{be}$  is simultaneously compensated.